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This report gives an overview of the experimental and theoretical research supported by ONR grant N00014-89-J-1714 from 1989 to 1995. The research focused on waves, transport, and equilibrium of magnetically confined single-species plasmas. Two new apparatuses were built: a laser-diagnosed ion apparatus targeted towards "test-particle" measurements of cross-field transport from long-range ion-ion collisions; and a camera-diagnosed electron apparatus which gives quantitative data on 2-dimensional fluid instabilities, vortices, turbulence and relaxation processes. Theory work provided support for the experiments, and developed several fundamental plasma effects, including rotational pumping transport, a 2D stability theorem, waves in finite-size ion plasmas, and the structure of ion crystals. These results have been published in 57 journal articles and 5 Ph.D. theses.

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Dear Chuck,

Enclosed are 3 copies of the Final Technical Report on our ONR Grant N00014-89-J-1714. Please let me know if you need further information.

Sincerely,

Fred

C. Fred Driscoll

CFD/jc

Copies to:

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Final Technical Report

"Pure Electron Plasmas Near Thermal Equilibrium"

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ONR support has enabled a highly productive program of experiments and theory on waves, transport, and equilibrium in single species plasmas. These single species plasmas are unique in that they can relax to global thermal equilibrium while confined in a simple cylindrical trap. In practice, this means that incisive quantitative measurements can be made on a variety of fundamental plasma processes, for direct comparison to theory predictions.

During this grant, two new apparatuses were developed and are now fully productive: a new laser-diagnosed ion plasma apparatus, called "IV," which allows quantitative measurement of test particle transport; and a new camera-diagnosed electron apparatus, "CamV," which gives high resolution images of 2D cross-field flows. Additionally, experiments were continued on the existing electron plasma containment apparatus "EV." Theory work developed fundamental ideas of waves, transport, and equilibrium in these systems, and supported the experiments.

In general, we have sought to obtain tests of plasma theory under the simplest possible circumstances we can devise; and, when the theory is inadequate, to develop it further. We now understand in detail some of the important processes which transport particles, energy and momentum across magnetic fields. Further, the wide range of parameters available in these systems has allowed us to understand which processes dominate in various parameter regimes.

The scientific results are fully described in the journal articles and Ph.D. theses. Here we give a brief overview and reference to the papers.

The electron experiments and theory work have focused on the rapid transport associated with 2D fluid vortices, instabilities, and turbulence. The 2D drift-Poisson equations governing the magnetized electron columns are mathematically identical to the 2D Euler equation governing inviscid, incompressible fluids such as water. Our initial experiments on nonlinear vortex dynamics and merger established that the electron columns evolve as fluid vortices, and are probably the most precise tests of fundamental fluid processes [1,4-7,9,15-16]. We have recently developed a technique to track the positions of the individual vortices using only received signals on the walls, and we believe this will enable even more quantitative understanding of processes affecting vortex dynamics [12].

Experiments on instability transport began with investigation of hollow electron columns which exhibit "diocotron" mode shear instabilities, which are the plasma analogue of Kelvin-Helmholtz fluid instabilities [2-3,8]. The instability undergoes nonlinear saturation with the formation of vortices, then the vortices move chaotically and appear as turbulent noise, and finally the noise decays leaving a reasonably quiet 2D quasi-equilibrium [17-18,23-28]. The collisional (or "viscous") transport to 3D thermal equilibrium then occurs on a much longer time scale.

Our recent experiments have provided insights into processes contributing to the relaxation of 2D fluid turbulence. Experimental characterization of "beat wave damping" established that this nonlinear process will symmetrize isolated vortices even in the absence of viscosity [14]. This process had not been considered in the fluids community, and is precluded in "contour dynamics" simulations. Our experiments on the relaxation of turbulence demonstrated that minimization of enstrophy gives a quantitative prediction of the relaxed meta-equilibrium for moderate energy initial conditions, providing a substantial challenge to theory [23].

Most surprisingly, recent experiments on CamV have shown that relaxation processes can be totally arrested by the formation of "vortex crystal" states, where the turbulent vortices have settled into a geometric pattern which lasts for up to 10^4 rotation times [26]. Here, the challenge to theory is to understand how the intense vortices give energy to the background of diffuse vorticity, and to understand whether the existence of these vortex lattice states fundamentally affects the chaotic dynamics and merger processes by which turbulence relaxes.

We have also extended the theory of the stability of these 2D plasmas. Our new 2D stability theorem provides a basis for understanding the longevity of various equilibria (observed by Fajans and others) when the confinement boundaries are not axisymmetric [9,10]. The traditional stability theorem of Davidson and Krall applies only to symmetric equilibria, but we find that the asymmetric equilibria are stable if the electrostatic energy is a *maximum* with respect to nearby states that are accessible under incompressible flow. This work has now been generalized to toroidal geometry [13].

The IV apparatus is now fully operational, equipped with two tuneable lasers. The laser-induced-fluorescence diagnostic routinely gives the temperature, density, and rotation velocity profiles of the Mg^+ ions, and the plasmas can be simultaneously cooled or manipulated with the second laser. The ion plasmas have an "anomalous" loss time of thousands of seconds, which is close to that expected from a dependence on the ratio of axial bounce time to rotation time and a theoretical mass scaling [50].

Interestingly, we have established that the ion plasma can be contained effectively "forever" by applying a rotating electric asymmetry to the walls [51]. In practice, the same ions are now contained with the same density and temperature profiles for up to 2 weeks, allowing accurate experiments. Further, we believe this technique may be very useful for other containment devices.

Most significantly, we have now demonstrated that the LIF diagnostics can measure test particle transport with time scales from $0.1\text{-}10^3$ seconds. Here, the atomic spins of certain ions are "tagged," and these particles are tracked as they move across the magnetic field. This gives unprecedented ability to quantify the underlying transport processes for comparison to theory,

especially since the measurements can be made repeatedly on a plasma which macroscopically is not varying with time. The enhanced transport expected from our theories is clearly being seen.

Our early experiments on the EV apparatus first observed the transport to confined 3D thermal equilibrium states. In the course of these experiments, we realized that traditional transport theory was implicitly based on an ordering of plasma parameters which does not apply to magnetically confined single-species plasmas. We developed a new transport theory for this case, which predicts that the rate of transport to thermal equilibrium is much faster and that the physics is very different. Essentially, the shear viscosity of the electron fluid is much greater than naively expected, and this viscosity may even be non-local. Understanding this transport would be a major contribution to basic plasma physics, and data now being taken from IV and EV will allow us to do so.

In other experiments on the cryogenic CV apparatus, we have measured the compressional, or bulk viscosity of the electron fluid [32,33,35]. Here, the length of a flux tube of plasma varies periodically as the plasma rotates, and compressional viscosity acts on this "rotational pumping" to cause relaxation towards 3D thermal equilibrium [31]. Quantitative agreement with theory is obtained over many decades in plasma parameters, making this the best-understood example of asymmetry-induced particle transport. This understanding is now being applied to other transport situations [34].

Ion-cyclotron wave experiments on IV revealed that the ion plasma contains both Mg^+ and Mg^{++}, and that significant cyclotron wave frequency shifts occur due to the presence of the second species [52,53]. The general signature is similar to that recently obtained by Gould for electron plasmas: an $l=1$ mode is observed slightly below Ω_c, and $l=2$ and $l=3$ modes are observed somewhat higher than Ω_c. Our multi-species analysis explains the $l=1$ downshift in terms of the Mg^{++}/Mg^+ ratio and the radius of the plasma, and thus can be used as a diagnostic for these parameters. We believe these experiments may contribute to understanding this ion cyclotron resonance technique for chemical mass analysis.

Many physics applications utilize ion plasmas at ultra-low temperatures, where liquid or crystal states are observed, and recent theory work has contributed substantially to our understanding of these states. Surface effects change the crystal structure when the dimensions of the crystal are less than a few 10's of interparticle spacings [36-38,40], which is typically the case in the experiments. As the external potentials vary and the overall shape of the plasma changes, the crystal undergoes structural transitions [44,45]. One important limit is the case where the charges are squeezed onto the trap axis by the external forces, forming a 1D Coulomb chain. These chains have been realized in experiments on storage rings and in Paul traps.

Thermal relaxation in strongly correlated plasmas is also being studied. For 1D chains in storage rings, the temperatures parallel and perpendicular to the chain axis relax towards one another at an exponentially slow rate set by the breaking of a many-particle adiabatic invariant [30]. A similar result has recently been predicted for the equilibration of transverse and parallel temperatures in a strongly magnetized strongly correlated plasma [29]. This extends our earlier thermal relaxation work for strongly magnetized plasmas into the regime of strong correlation.

The collective electrostatic modes of cold nonneutral plasmas are also a subject of great current interest. We have developed an analytic theory that predicts the mode frequencies for such plasmas, including the effect of strong correlation on the modes [39,41-43,47-49]. Excitation of the modes can provide a useful nondestructive diagnostic of plasma properties such as density and plasma shape. Modes have also been implicated in transport processes leading to loss of the plasma and limits on the density. Our theoretical work on strong correlation effects on the mode frequencies may also provide an experimental method to determine the shear and bulk moduli of a strongly correlated plasma, which is of interest to a range of disciplines including astrophysics and condensed matter physics.

PUBLICATIONS LIST, ONR N00014-89-J-1714
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2D Fluid Dynamics

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